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On the Absorption of Wave Power Using Ship Like Structures

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ABSTRACT

This paper presents a conceptual study of a wave farm based on ship-like structures being developed under the acronym KNSWING. These are attenuator Wave Energy Converters (WEC) integrating Oscillating Water Columns (OWC) with side openings in the hull. This leads to important advantages compared to solutions based on Point Absorbers as described in (K. Nielsen, 2004) such as: large modular structures with redundant PTO systems, simplicity with few moving parts, less electrical equipment on the seabed and lower grid connection costs, a main structural frame suited for mass production, high energy absorption from waves, low mooring forces, low cost concerning tow out for installation, and easy access to mechanical equipment which are all located above water.

KEY WORDS: Wave energy; cost of energy; Wave Energy Converter WEC; Attenuator OWC; Experimental performance assessment; Marinet experiments; Numerical Modelling; Mooring Loads; North Sea; Conceptual design; Technology Performance Level TPL; Concrete structures; Cost of energy LCOE.

INTRODUCTION

The objective of this paper is to present a conceptual study of the design of a wave farm composed of a large number of serially produced Wave Energy Converters (WECs) and the experimental and theoretical results related to the development of a ship-like structure to absorb wave energy. The concept was first investigated following the energy crises in 1973, when the UK set out research to develop alternative energy solutions converting wave energy to electricity to meet part of the UK electricity demand. A wide range of WEC's resulted from this R&D programme presented at the first international conference of

Wave Energy in 1979 in Gothenburg. Among these ideas was a ship-like concept the I-beam OWC attenuator concept (Moody, 1979), which had been tested at University of Edinburgh by Stephen Salter, but also the Kaimai an 80 meter long ship with OWC chambers which had been tested in real seas in Japan was presented.

The attenuator principle is one of three main WEC configurations as shown on Fig.1. Compared to point absorbers and terminators the attenuators face the waves with their bow and span several wave lengths which provide a stable reference with minimal drag and mooring forces.

In recent paper on attenuators, Stansell and Pizer (2013) describe how additional length would provide additional power in relation to swept volume. This inspired the main author of this paper to reinvestigate the power absorption, design and survivability of ship-like structures and apply to the EU Marinet test programme together with DTU.

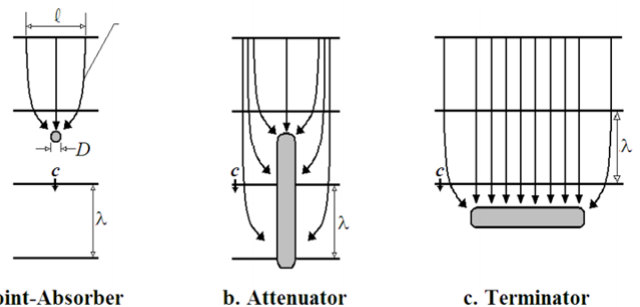


Figure 1 Typical Wave Energy Converter configurations

The experimental investigation of the wave energy converters was carried out at HMRC at UCC in Ireland, followed by additional Marinet experiments in Portaferry QUEB in combination with two student projects at DTU. Based on the results from the experiments and

numerical calculations for the system on energy absorption and mooring loads, a conceptual design study is presented.

CONCEPTUAL DESIGN OF THE KNSWING

The KNSWING WEC shown in Fig. 2 is a 240 meter long ship-like structure with Oscillating Water Columns (OWCs) along its sides. The structure is proposed to be built in concrete to make the structure less expensive compared to a structure built in steel. A serial production using a continuous forming technique similar to the methodology to be used at the Fehmarn Belt tunnel project is proposed. Located at strategic sites such production facilities could be maintained for several years supplying WECs to designated locations.

The size of the wave farm depends on how many structures will be deployed side by side in an array. The WEC should be optimised to suit the specific site i.e. the Danish part of the North Sea or more exposed Atlantic sites or any other location with suitable wave conditions and infrastructure.

The wave energy is absorbed by the OWC chambers in which the water oscillates up and down. This up and down motion of the water in each chamber pushes and pulls air in and out via air turbines that drive electrical generators. High efficient air-turbines suited for the conversion are under development in Portugal (Falcão, 2015).

The wave energy converter is moored at the bow of the structure using a turret mooring system – and an additional optional mooring line can be attached to the stern (aft) for practical or safety reasons. The wave energy converter is intended to turn itself towards the incoming waves – but a slight angle to the wave can often increase the overall absorption by increased absorption on the side facing the incoming waves.

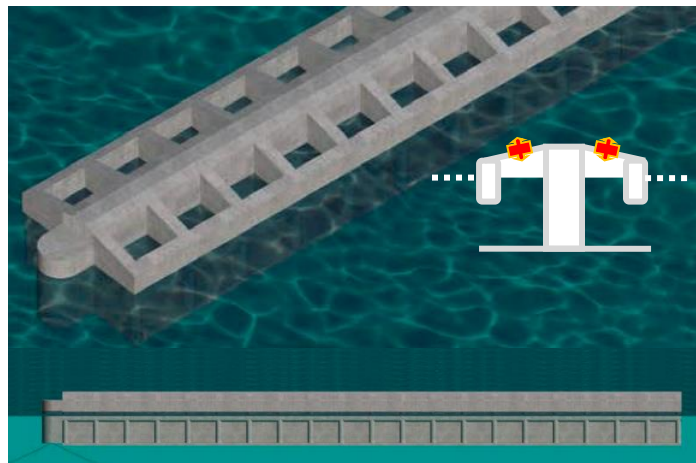


Figure 2 Impression of the KNSWING WEC Concrete Structure

Main data and dimensions of the KNSWING WEC structure are shown in Table 1 for two different characteristic length 150m and 240m long.

Table 1 Main dimensions and data of the proposed structure

KNSWING	L=150m	L=240m
Rated absorbed Power @ $H_s = 5\text{m}$	2500 kW	10000 kW
Annual absorbed energy (North Sea)	6.557 MWh	13601 MWh
Length L	150 meter	240 meter
Beam B	19.5 meter	28.80 meter
Height H	12 meter	16.8 meter
Beam of buoyance chamber b	6.5 meter	8 meter
Draught D	8 meter	12.8 m
Freeboard:	2.5 meter	4 meter
Weight	12.000 ton	45.000 ton
Displacement	12.000 m ³	45.000 m ³

LOCATION IN THE NORTH SEA

The wave energy resource increases with the distance from shore and in the central part of the Danish Part of the North Sea. At 200 km distance from the west coast of Jutland the wave energy resource reaches about 16 - 24 kW/m (Ramboll, 1999). The water depth at this distance is typically between 40 and 60 meters and the maximum wave conditions with a significant wave height of about $H_s=12$ meters.

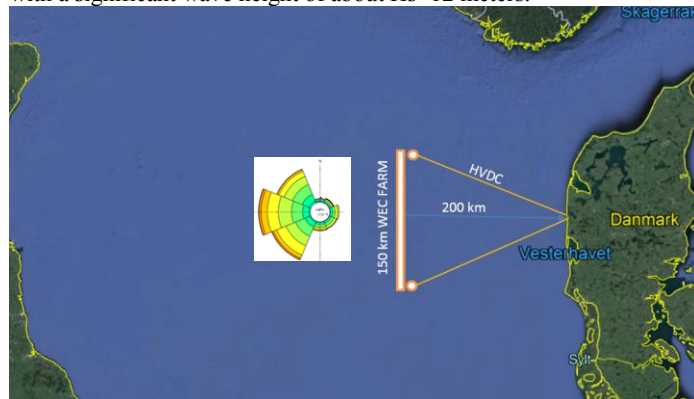


Figure 3 Location of a conceptual 150km long WEC farm located 200 km from shore in the Danish part of the North Sea. Also the directional distribution of waves are indicated with a wave rose.

As an example, a 1400 MW wave energy plant up to 150 km long is indicated on Fig. 3. This wave plant consists of 7 modules of 200 MW offshore transformer platforms and to which WECs are electrically connected. An additional two platforms equipped with HVDC equipment are located at each end converting the electricity from the seven transformer platforms to DC power and transmitting it to the shore over a distance of 200 km.

Other interests at sea such as oil and gas production, fisheries and transportation must be considered in order to get the necessary permits for energy production.

CONCRETE PRODUCTION FACILITIES

It is important for cost efficiency that the attenuators can be built in series production. This could be achieved by adopting the production and installation methodology used at projects such as the tunnel element fabrication of the Fehmarn Belt crossing illustrated in Fig. 4.

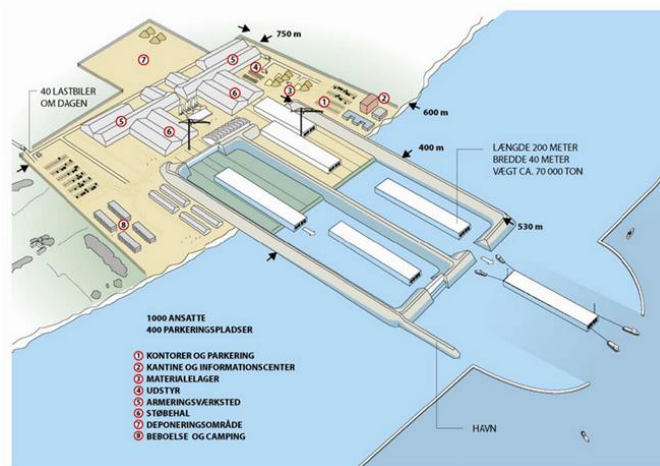


Figure 4 Fehmarn Belt Concrete fabrication facilities

The cost of reinforced concrete produced in such a rational way is estimated in the order of 260 \$/ton. With a production speed of 5000 m³ (12500 ton) concrete/week it will take one week to build one WEC unit of 150 meter and about 3.75 weeks to build the 240 meter version.

POWER TAKE OFF (PTO)

The conceptual design of the WEC includes 40 air turbine-generators, converting the wave-induced pneumatic power into electricity. The airflow reverses its direction twice in a wave cycle, the amplitude of each wave is largely random and the power varies with the sea state. The twin-rotor air turbine concept illustrated in Fig. 5 developed by Antonio Falcao is so far the most efficient self-rectifying air turbine, proposed and tested, with a peak efficiency of 85% (Falcão 2015).

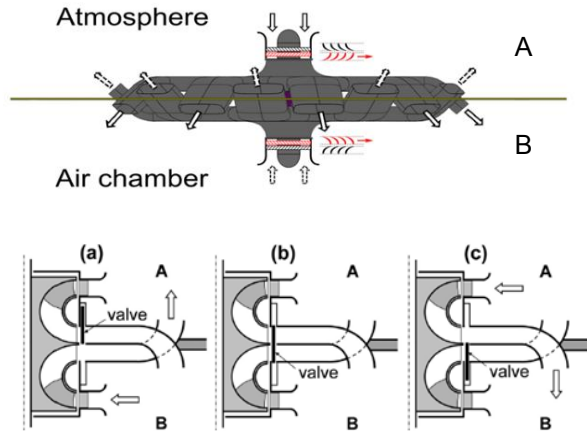


Figure 5 Twin-rotor self-rectifying turbine

The PTO technology is not completely developed, but it has the potential to integrate sub-optimal control. Latching control implies that the airflow is blocked for a period to allow pressure (or vacuum) to build up and then letting the air flow with greater pressure and velocity – leading to increased power absorption. Control of a multi-element wave energy converter is a complex task, and control requires some prediction of the excitation forces. In this case the row of OWC columns placed after each other, allows the pressure monitored in the front chambers to be used for prediction of the excitation upon the following ones.

The valve position shown in (Fig. 5a) allows the airflow to flow out of the OWC chamber, and (Fig. 5c) position allows the air to flow into the OWC chamber maintaining the same direction of rotation on the turbine and generator. To implement control strategies for the air flow/water column motion Fig. 5.b shows the valve position that can close the in- and outlet flow for a fraction of the wave period. The closed position can also be used for safety reasons ($H_s > 8.5$ m) or for maintenance.

In sea conditions with $H_s \geq 5$ m the WEC will deliver the rated power – the rated power is the average power produced over 30 minutes. Power peaks might occur for short durations associated with individual waves, this might temporary “overload” of the individual generators. The rated power definition is used to normalize the CAPEX.

The 40 air turbines on the WEC each drive a variable speed generator. The power from each generator is rectified to DC and stored in a battery. Before transmitted from the WEC the power is converted back to AC and transformed to 11kV before being transmitted from the WEC to the sea bed via the umbilical shown on Fig. 9.

MOORING

The mooring system is being analyzed as part of a Danish Research Project “Mooring Solution for Large Wave Energy Converters” led by Aalborg University in which mooring solutions for four different WECs are being investigated (Thomsen et al., 2015 and Thomsen J.B, 2016). The use of synthetic ropes for mooring materials is being investigated and a scale model of such a mooring system has been tested on the KNSWING as part of the second round of Marinet. A conceptual design of the mooring system is shown in the Fig 6.

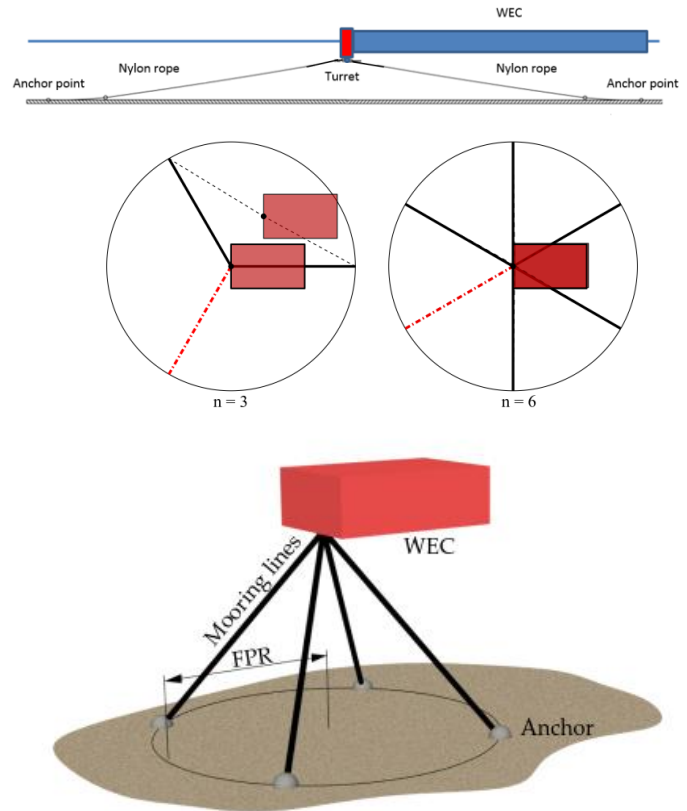


Figure 6 The conceptual design of the turret mooring system

The mooring system is composed of 6 mooring lines of synthetic rope with a length of 200 m. A numerical model of the KNSWING has been developed using the software package OrcaFlex (Orcina, 2016) and the BEM code NEMOH (Barbarit 2015).

The survival condition was modelled using the Northsea design conditions with a sea state of 50 year return period with $H_s = 9.9$ m and $T_p 14.1$ s combined with a wind velocity of 39.9 m/s and current of 1m/s. All environmental loads were assumed to act in the same direction. The WEC was allowed to surge 44 meter with a waterlevel variation of 1,6 meter. The model assumed the use of a braided nylon rope with a non-linear stiffness curve corresponding to a Viking Braidline Nylon rope Ø198mm (Bridon, 2016). Based on these assumptions a maximum mooring load of 2456 kN was calculated leading to a safety factor of 3. An optimization routine was subsequently applied to the KNSWING to find optimal mooring layout (Thomsen et al., 2018). Longer lines lead to a softer mooring system and smaller loads, but this must be balanced against increased cost and WEC spacing requirements. The moorings are on a conceptual level attached to drag embedded anchors.

INSTALLATION

The deployment plan includes the following major operations:

1. Installation of Grid connection cable(s) to shore
2. Installation of Transformer Platforms at site
3. Installation of mooring piles for the array
4. Interconnection cables for the WECs to platforms
5. Interconnection cables between the platforms
6. WEC Tow-out and connection to moorings and umbilical cables

The WEC will be towed in position using a combination of tugboats and possibly its own propulsion unit. With a speed of 6 knots (12 km/h) it will take about 20 hours from production facility to location. The installation of the mooring system will need to be developed in such a way that this is prepared and ready for attachment of the WEC.

GRID CONNECTION

The components involved in collecting the power from the WECs are called the Wave Power Aggregation system and the part that transmits the aggregated power is called the Electrical Wave Power Delivering system. To create an overview, the parts involved in the Wave farm have been given an identification number as shown in Table 2.

Table 2 Identification system for the Wave farm

ID	System, Subsystem, Component	Function
01	<u>WEC DEVICE</u>	Convert wave energy into transportable energy
02	<u>WAVE POWER AGGREGATION SYSTEM</u>	Aggregate power from the different WEC devices
0200	Dynamic electrical cables	Umbilical transport power from WEC to sub-sea hubs
0210	Sub-sea hubs	Aggregate power from WEC
0220	Intra-array electrical cables	Transport power from sub-sea hub to next hub's and ultimately to Platform
0221	cables to platform	2*2.0 km 36kV 20.000kVA
0222	cables to platform	2*3.8 km 36kV 20.000kVA
0223	cables to platform	2*5.6 km 36kV 20.000kVA
0224	cables to platform	2*7.4 km 36kV 20.000kVA
0225	cables to platform	2*9.2 km 36kV 20.000kVA
0230	Substation/Platform	Platform that aggregate power from the inter array cables and supports the Trafo/Breaker
0240	Trafo station	Trafo/Breaker 36/160kV 200MVA
0250	Intra-array electrical cables	20 km Transport power from previous Platform to next 160kV
03	<u>ELECTRICAL WAVE POWER DELIVERING SYSTEM</u>	Deliver electrical power to the grid at Point of Connection
0310	HVDC offshore converter station	Platform Offshore transformer (160/400kV) to convert 1400 MW to HVDC (depending on the distance)
0320	Export cables	250 km DC cable to the shore
0330	HVDC Onshore substation	Transform from DC to AC Condition power for delivery to the grid

ID 0200 the Umbilical Cable from the WEC is shown on Fig. 7 and is attached to the front of the WEC at the turret, and connected to a subsea junction box and transformer 6kV/36kV. The umbilical will be designed to export the rated power P_{rated} from the WEC at a voltage of about 6kV suited to the architecture of the Umbilical.

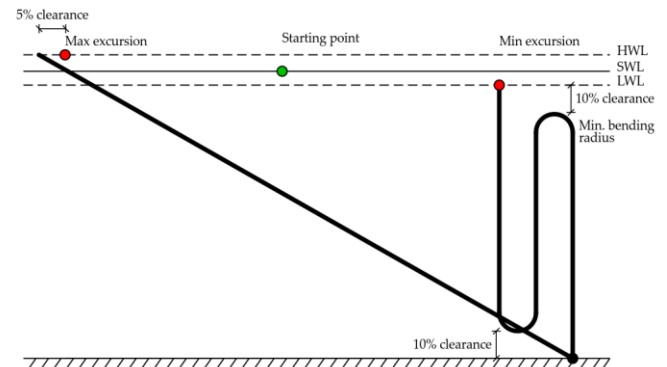


Figure 7 ID 0200 The umbilical

The ID 0210 submerged connectors and transformers (6/36 kV) connect to ID 0220 Inter array submerged electrical cables of 36kV. ID 0221 to 0225 indicate that the submerged cables are of incremental length (to each side of the aggregation platform) to collect wave power over a distance of 20 km and deliver a maximum of 20 MW to a fixed offshore 200 MW transformer platform ID 0230. On the platforms are placed Transformer Breaker of 200 MVA given the ID 0240. The above description is illustrated on Fig. 8. The number of platforms depends on the total size of the Farm.

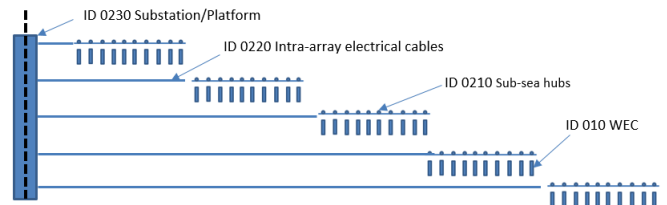


Figure 8 The inter-array power aggregation system connecting the WECs to the Substation/Platform ID 0230

The aggregation platforms are interconnected with ID 0250 160 kV AC power cables designed to transport the total rated power of the plant. The design of the Electrical Wave Power Delivering System ID 03 will depend on the location and the distance to shore. In cases with a distance larger than about 150 km, a High Voltage Direct Current (HVDC) connection is proposed. If in addition the wave farm is very large, two cables are proposed to transmit the full power to shore (as shown on Fig. 3) thereby giving a redundancy in the power delivering system. In this case the offshore platform ID 0310 includes, transformer and converter station including the HVDC conversion equipment. The DC power cables ID 0320 are designed to transport the full rated power of the plant at 400 kV. It is also possible that the HVDC transmission scheme connects with another country and thereby enables power to be transmitted between countries in both directions when and if the wave power plant is not running at its full capacity. On the shore a HVDC station ID 0330 is connecting the farm to the land based grid.

WEC FARM MAINTENANCE COST AND AVAILABILITY

The target cost of maintenance per year is about 2% of the CAPEX and the target availability is 98%. This requires a suitable choice of durable components combined with a strategic proactive maintenance plan.

The maintenance requirements of the WEC farm are typically related to the mechanical components with a lifetime smaller than the design life of the structure. This is the turbo machinery, the electrical equipment and the mooring system.

The turbo equipment is foreseen to be periodically removed for overhaul and replaced with newly maintained turbine/generator units. The electrical equipment will be checked in relation to each overhaul – and the mooring system monitored for tension in order to predict maintenance.

PERFORMANCE

Depending on the target location, different generic linear relationships between significant Wave Height H_s and Average Wave Period T_z can be found to make an initial estimate of the device performance at a specific location. Testing in just five sea states representing the most frequently occurring sea states can provide a relatively accurate picture of the device performance at that site as described in the report under IEA-OES (Nielsen & Pontes 2010). A linear relation between the most frequent wave period $T_{e\text{ ave}}$ and the significant wave height is proposed as $T_{e\text{ ave}} = A \cdot H_s + B$ [sec] relations for other sites such as Belmullet, Norway, Atlantic and the North Sea. A summary of the calculated performance combining the generic sea conditions with measured energy absorption is shown in Table 3.

Table 3 Calculated performance based on scaled up test results to the L=240 m and L=150 m KNSWING at different generic ocean sites.

	Belmullet	Norway	Atlantic	North Sea
P_w Resource [kW/m]	72	42	26	20
Eabs $L=240$ [MWh/year]	30188	22504	16160	13601
ACWR $L=240$	0.20	0.25	0.30	0.32
CF $L=240$	0.34	0.26	0.18	0.16
Eabs $L=150$ [MWh/year]	12772	9960	7867	6557
ACWR $L=150$	0.13	0.18	0.23	0.25
CF $L=150$	0.42	0.32	0.26	0.21

The Average Capture Width Ratio (ACWR) is calculated as

$$ACWR = \frac{Eabs}{P_w * L * 8760} \quad (1)$$

the average absorbed energy $Eabs$ [kWh/y]

the average incident wave power resource P_w [kW/m]

the length of the structure L [m]

hours over a year (8760)

The Capacity Factor CF is calculated as:

$$CF = \frac{AEP}{P_{rated} * 8760} \quad (2)$$

AEP is the Annual Energy Production from the Farm

P_{rated} is the rated power of the plant (200MW)

LEVELICED COST OF ENERGY (LCOE)

The cost of energy calculation is important even at an early stage of development to quantify the cost and identify the cost centres of the WEC farm as described in the OES LCOE study (OES 2015).

The cost of an array of 200 MW has been considered, and the cost of energy is simplified to the estimation of CAPITAL EXpenditure (CAPEX), OPERational EXpenditure OPEX and Annual Energy Production AEP combined with a financial interest at Fixed Charge Rate FCR cost

$$LCOE = \frac{CAPEX * FCR + OPEX}{AEP} \quad (3)$$

The Rated Electrical Power is calculated based on measured absorbed power in a scaled sea condition of $H_s = 5$ m and the assumed PTO conversion efficiency (at this stage 50%). Based on this value, the number n of WECs needed to build a 200 MW wave farm is calculated. In Table 4 below it is seen that it will require 40 WECs of length $L=240$ m and 114 WECs of 150 m. The length of the 200MW installation assumes that each device is placed side by side with one device length interspacing ($n * L$).

The AEP per WEC is based on the values derived from model experiments as shown in Table 3 for the North Sea location. The annual energy production of the farm is calculated by multiplying with the number of devices and their PTO efficiency and availability.

Table 4 per 200 MW wave farm module

KNSWING	L=150m	L=240m
Rated Electrical Power of WEC Plant (MW)	200	200
Number n of WECs installed	114	40
Maximum absorbed Power per WEC [kW] (at $H_s=5.5$ meter)	3500	10000
Rated Electrical Power per WEC [kW] (at $H_s=5.5$ meter)	1750	5000
Annual absorbed Energy per WEC (MWh/y)	6557	13601
Distance to shore (km)	250	250
Water depth (m)	45	45
Length of installation (km)	17	10
Mean Resource Level (kW/m)	20	20
PTO efficiency%	50%	50%
Availability%	98%	98%
AEP Annual Energy Production MWh/y	367.192	266.580

CAPEX (*1.000.000 \$) (1\$=6DKK)	L=150 m	L=240 m
Project development and production facility	79	79
Structure and prime mover	411	528
Power Take-off	83	83
Moorings and Foundations	86	107
Installation	50	67
Grid connection (200 km)	333	333
CAPEX Total	1043	1197

Project lifetime (years)	25	25
OPEX (50% CAPEX/lifetime)	18	21
FCR (%)	10%	10%
AEP [MWh/y]	367.192	266.580
CF	0.21	0.15
LCOE \$/kWh	0,33	0,53

TECHNOLOGY PERFORMANCE LEVEL (TPL)

The described KNSWING system was used as an initial test case in the Structured Innovation/Wave-SPARC Project by NREL and Sandia in the US for the development of a TPL assessment methodology. The origin of this methodology is described by Weber (2012, 2013) and has been further developed with respect to questions about stakeholder capabilities as described in (Barbarit et al. 2017). Each capability is divided into a number of sub and sub-sub capabilities which from a stakeholder point of view can be evaluated with a score from 1 – 9. The score of each capability is then combined into an overall TPL score as shown in the summary Table 5 below. The performance level in this case to a score of 7.1 based on the combined individual capabilities.

Table 5 Technology Performance Level TPL assessment of Capabilities

Summary: KNSWING 2016, TRL 1-2		
	Technology Performance Level:	
C1	Have market competitive cost of energy	6.1
C1.1	Have as low CAPEX as possible	7.0
C1.2	Have as low an OPEX as possible	6.7
C1.3	Be able to generate large amount of electricity from wave energy	4.7
C1.4	Have high availability	7.2
C2	Provide a secure investment opportunity	5.7
C2.1	Be survivable	5.1
C2.2	Be low risk under design conditions	6.3
C3	Be reliable for grid operations	7.5
C4	Be beneficial to society	7.9
C5	Be acceptable for permitting and certification	9.0
C6	Be acceptable w.r.t safety	7.3
C7	Be deployable globally	9.0

The assessment was in this case done by the developer (main author of this paper). Experts are currently testing the TPL assessment methodology to develop it further toward a robust, unbiased evaluation methodology suitable for industrial guidance and use (Bull, et al. 2017).

EXPERIMENTAL/THEORETICAL DEVELOPMENT

The performance and mooring loads have been developed using a combined experimental and numerical approach. In this section some of the experimental results are presented.

Fig. 9 and 10 shows the experimental model built in wood, it is 3 meter long and including 40 OWC chambers (20 on each side). The damping to be applied by the air turbine to each chamber is modelled by a hole in the roof of each OWC chamber with an area of about 1 % of the chamber water surface area ($\varnothing 14$ mm).

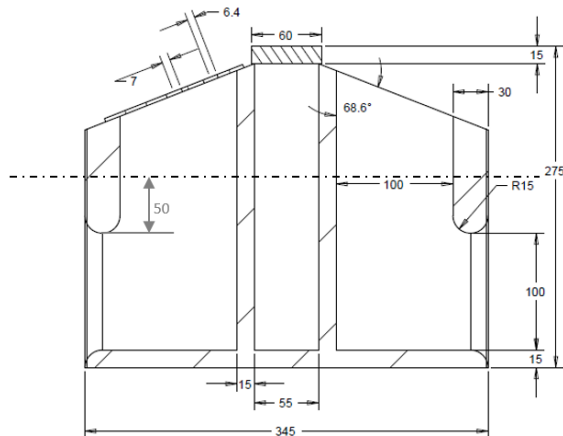


Fig 9 Cross-section of the experimental model numbers in mm.

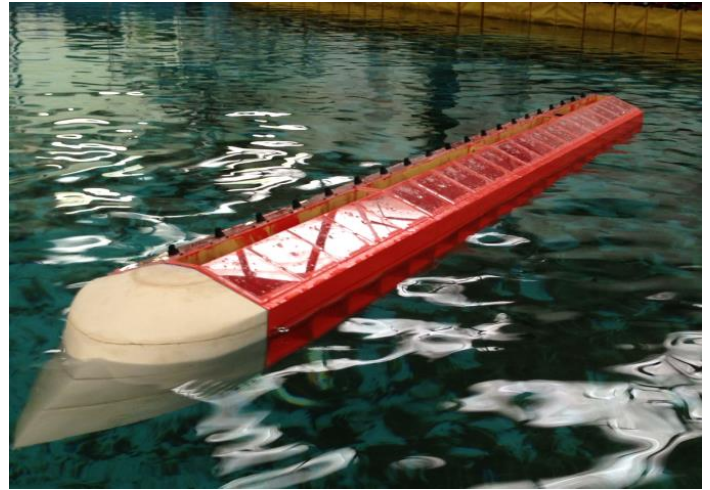


Figure 10 The experimental model

The initial tests were conducted at HMRC basin Ireland in 2013 and in 2015 two rounds of testing were carried out at QUB shallow water basin in Portaferry to further investigate survival, mooring design and optimization. Using the same physical model and model sea conditions at both locations a comparison between the results obtained at the 1m deep HMRC basin and the 0.55m deep Queens facility was possible. This can be seen in Fig. 11 as a difference between the blue (0.55m deep) and dashed green curve (1.0m deep)

Experimental Setup & Variables Measured

The waves were measured using four wave probes. The motion of the WEC was monitored using a motion tracking system. The time series included 2^{11} data points with a sample period of 0.031 sec. The experiments were structured in a series of regular and irregular waves.

The regular wave experiments of different periods and heights were prepared in three groups of constant steepness (H/λ constant). However, the waves generated in basins with different depth result in different wave length for the same wave period. A wave with period $T=2$ seconds and a steepness of 2.5 % will in the 0.55m deep basin have a length $\lambda=4.2$ m, height 0.105m and energy flux 23.9W/m compared to $\lambda=5.2$ m, wave height 0.130m and energy flux 39.0W/m the 1m deep basin. Experiments and theory (Fig. 11) indicate that the Capture Width Ratio CWR is about twice as high in the shallow wave basin for these longer wave periods of constant steepness. For shorter wave periods (< 1.5 second) results are very similar from both locations.

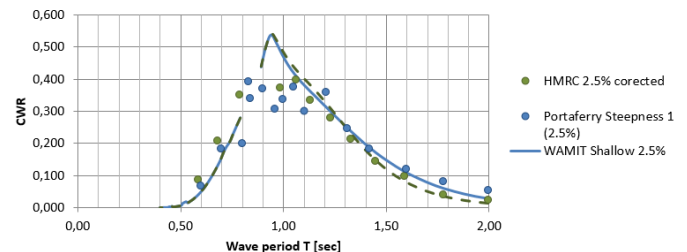


Figure 11 CWR in regular waves of steepness 2,5%

The influence of water depth on the wave length, group velocity and power are fundamental and important to include when planning scale experiments that replicate a certain location. Also in relation to replicating the mooring geometry, the water depth is very important.

Theoretical and numerical validation

Following the initial testing at HMRC a numerical model was developed for the system (Ducasse, 2014) and further described in (Bingham, 2015) for comparisons with the performance in regular waves. The 40-chamber I-Beam attenuator-type, oscillating water column, wave energy converter is analysed numerically based on linearized potential flow theory, and experimentally via model test experiments. The high-order panel method WAMIT by Newman and Lee (WAMIT; 2014,) is used for the basic wave-structure interaction analysis. The damping applied to each chamber by the power take off is modelled in the experiment by forcing the air through a hole with an area of about 1 % of the chamber water surface area. In the numerical model, this damping is modelled by an equivalent linearized damping coefficient which extracts the same amount of energy over one cycle as the experimentally measured quadratic damping coefficient. The pressure in each chamber in regular waves of three different height-to-length ratios is measured in the experiments and compared to calculations. The model is considered in both fixed and freely floating, slack-moored conditions. Comparisons are also made to experimental measurements on a single fixed chamber. The capture width ratio CWR express the Absorbed Power by the device over the incoming wave power over a wave front with the same length as the length of the device. The absorbed power is in each experiment calculated based on the pressures measured in the OWC chambers. Fig. 11 show a good agreement between the calculations and the experiments. The irregular wave experiments were divided into 6 different series as shown in Table 6, which would enable investigation of different aspects related to seakeeping and performance and survivability, such as influence of spectral shape, directional spreading and wave period variations at constant H_s .

Table 6 Test series of irregular waves

Series 1	Long crested Brechtschneider Spectrum
Series 2	Spectrum Variation of Period
Series 3	Long crested JONSWAP
Series 4	Short crested
Series 5	Variation of spreading
Series 6	Survival conditions

In general, the results of the scaled-up performance showed in (Fig. 12) confirmed a good agreement between measurements carried out in Portaferry and experimental results obtained at HMRC. At both test locations the experiments showed that the structure absorbed 30 - 50% more power in short crested irregular waves (wave spectrums that included directional spreading) compared to long crested waves.

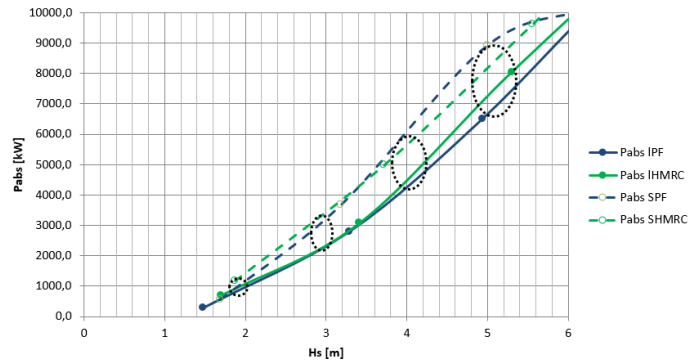


Figure 12 The experimental results in irregular waves

Mooring Geometry and Survival conditions

The chosen experimental mooring geometry was simplified into three elastic lines as shown in (Fig. 13), two lines to the front facing the waves and one line to the aft.

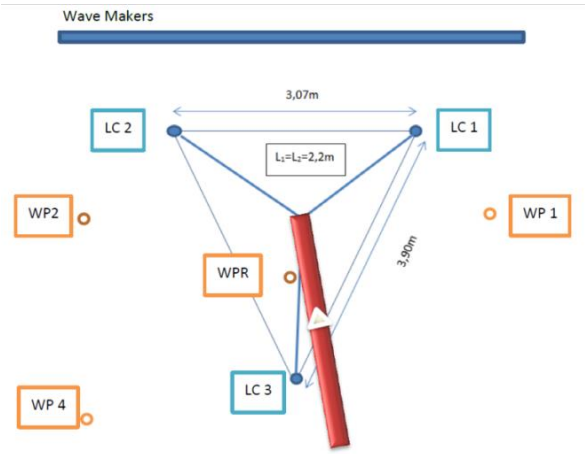


Figure 13 The experimental mooring setup and measured loads

The three lines were attached to the bow of the model and via a string and a pulley mounted in the basin floor connected to the load cells hanging from the gantry above the basin. The mooring lines were constructed from calibrated rubber cords and different stiffness's of mooring lines were tested and a relation between the maximum load and the stiffness and the pre-tensioning was obtained and described in the Marinet report (Nielsen K. 2013). The combination of H_s and T_z shown in (Fig. 14) below formed the survival waves to which the mooring system was tested.

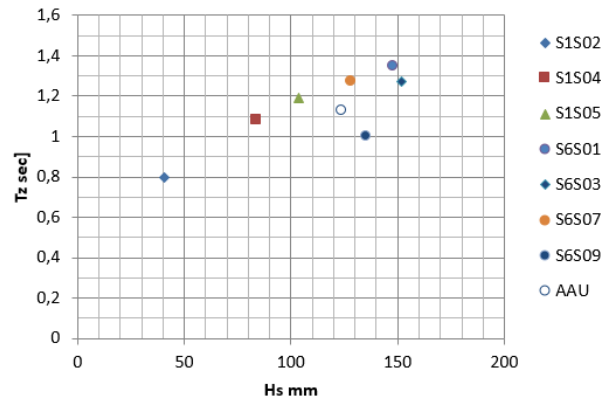


Figure 14 The combinations of H_s and T_z which were used for generating the “survival” wave conditions.

CONCLUSIONS

The KNSWING concept described in this paper is at an early Technological Readiness Level TRL between 1 and 3. Numerical models and small scale experimental models have been used to evaluate the performance and design loads. The concept has also been assessed using an early version of the Technology Performance Assessment Methodology giving a score of TPL=7,1 which can be combined with an estimated LCOE of around 0.33 \$/kWh.

From this TPL assessment, the areas which require further R&D are related to generating large amounts of electricity – that means

demonstrating that the conversion efficiency can be increased above 50% and further that the structural design is survivable – that means how the mooring system and concrete structure and reinforcement should be designed to deal with the expected loads.

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